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FAST TRACK PAPER

# Crustal concealing of small-scale core-field secular variation

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## SUMMARY

The Earth's magnetic field is mainly produced within the Earth's liquid and electrically conducting core, as a result of a process known as the geodynamo. Many other sources also contribute to the magnetic signal accessible to observation at the Earth's surface, partly obscuring the main core magnetic field signal. Thanks to a series of very successful satellites and to advances in magnetic field modelling techniques, considerable progress has, however, been made in the recent years toward better identifying the signal of each of these sources. In particular, temporal changes in the field of internal origin happen to be detectable now in spherical harmonic degrees up to, perhaps, 16. All of these changes are usually attributed to changes in the core field itself, the secular variation, on the ground that the lithospheric magnetization cannot produce such signals. It has, however, been pointed out, on empirical grounds, that temporal changes in the field of internal origin produced by the induced part of the lithospheric magnetization could dominate the core field signal beyond degree 22. This short note revisits this issue by taking advantage of our improved knowledge of the small-scale field changes and of the likely sources of the lithospheric field. We rely on a simple extrapolation of the observed spatial spectrum of the field changes beyond degree 16 and use a forward approach based on a recent geological model of lithospheric magnetization. This leads us to confirm that the main cause of the observed changes in the field of internal origin up to some critical degree, $N_C$, is indeed likely to be the secular variation of the core field, but that the signal produced by the time-varying lithospheric field is bound to dominate and conceal the time-varying core signal beyond that critical degree, in very much the same way the permanent component of the lithospheric field dominates and conceals the permanent component of the core field beyond degree 14. All uncertainties taken into account, we estimate $N_C$ to lie between 22 and 24. We, however, also note that in practice, the main limitation to the observation of the core field small-scale secular variation is not so much its concealing by the field of lithospheric origin but its fast changing nature and small magnitude. This leads us to conclude that whereas cumulative small-scale lithospheric field changes might be detected some day, detection of core-field secular variation beyond degree 18 is likely to remain a severe challenge for some time.

**Key words:** Dynamo: theories and simulations; Magnetic anomalies: modelling and interpretation; Satellite magnetics.

## 1 MOTIVATION

The recent decade has seen considerable improvement in our ability to identify the various signals that contribute to the observed geomagnetic field (for a recent review, see Hulot *et al.* 2007). In particular, thanks to the launches of the two satellite missions, Oersted in 1999 (Neubert *et al.* 2001) and CHAMP in 2000 (Reibger *et al.* 2002), both of which are still providing data, impressive progress has been made in our ability to build more and more detailed spherical harmonic models of the temporal changes of the field of internal origin. In a few decades, the spatial resolution of such models (in terms of resolved spherical harmonic degrees) has progressively changed from approximately degree 5 when only using data from the early but short-lived Magsat 1980 mission (e.g.

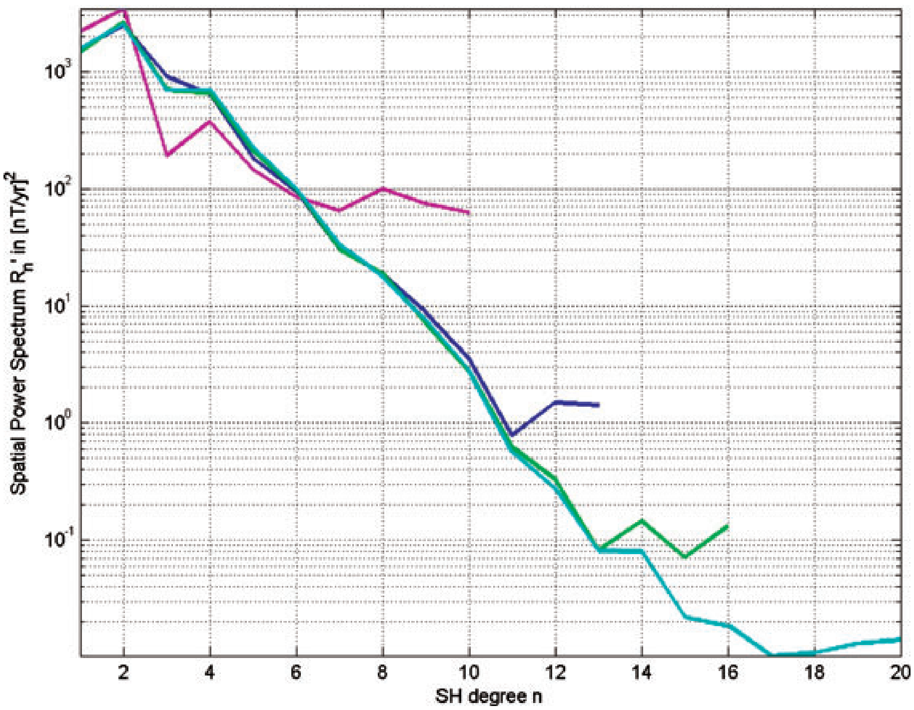


**Figure 1.** Mauersberger–Lowes spectra of the secular variation at the Earth's mean radius ($r = 6371.2$ km) as modelled by a series of models with increasing spatial resolution [units are (nT yr$^{-1}$)$^2$]. Pink, model of Langel & Estes (1985) for epoch 1980; Dark blue, model of Olsen (2002) for epoch 2000; Green, Model of Maus *et al.* (2005) for epoch 2002.5; Light blue, xCHAOS model of Olsen & Mandea (2008) for epoch 2004.

Langel & Estes, 1985), to progressively 10 (e.g. Olsen 2002), 12 (e.g. Maus *et al.* 2005; but see also Sabaka *et al.* 2004 and Lesur *et al.* 2008) and now perhaps 16, as suggested by the most recent xCHAOS model of Olsen & Mandea (2008). Fig. 1 illustrates those improvements, the signature of which can be measured by the increase in the degree beyond which the Lowes–Mauersberger spectra of those models at the Earth's mean radius (as defined by Mauersberger 1956; Lowes 1974) change from their common decreasing linear trend (with increasing degree $n$) to a flat behaviour, characteristic of noise-contaminated spherical harmonic coefficients.

Changes in the field of internal origin very likely reflect magnetohydrodynamic processes within the Earth's liquid, convecting and electrically conducting core, where the geodynamo is operating. Progress in modelling the temporal changes of the field of internal origin is thus of considerable interest to the investigation of core dynamics (see e.g. Hulot *et al.* 2002; Jackson 2003; Holme & Olsen 2006; Pais & Jault 2008; Olsen & Mandea 2008). Such investigations are, however, currently limited by the fact that the lithospheric field conceals the permanent component of the core field beyond degree 14, which makes it difficult to take full advantage of the recent progress in the resolution of core field change models (Hulot *et al.* 1992; Eymin & Hulot 2005; Pais & Jault 2008). But there is good hope that when longer times-series of high-resolution core-field change models are available, those limitations could be circumvented by, for instance, relying on data assimilation strategies inspired from those recently proposed by, for example, Fournier *et al.* (2007) and Liu *et al.* (2007).

One limitation that such approaches, or any other type of investigations of the core field, would, however, still have to face is the fact, first pointed out by McLeod (1996), that the time-varying component of the lithospheric field is also bound to dominate the time-varying component of the field of internal origin beyond some critical spherical harmonic degree. McLeod (1996) estimated this degree to be of about 22. But he relied on rather arbitrarily parametrized estimates of both the core and lithospheric field spatial and temporal power spectra. In what follows, we revisit this issue and take advantage of our improved knowledge of both the temporal changes of the field of internal origin and the sources of the lithospheric magnetization.

## 2 LITHOSPHERIC CONTRIBUTION TO THE TEMPORAL CHANGES OF THE FIELD OF INTERNAL ORIGIN

Progress in modelling the various sources of the Earth's magnetic field has also led to improved maps of the so-called magnetic anomalies produced by the magnetization of the lithosphere and crust (for a recent review, see Purucker & Whaler 2007). In particular, the accumulation of excellent data from the low orbiting (350–450 km) CHAMP satellite over the past 8 yr has stimulated the production of a series of spherical harmonic models, with increasing maximum degrees and resolution, though, as correctly pointed out by one of the reviewers, higher maximum degrees does not necessarily imply improved resolution and accuracy (Maus *et al.* 2002; Sabaka *et al.* 2004; Maus *et al.* 2006; Olsen *et al.* 2006a; Thébault 2006; Thomson & Lesur 2007; Lesur *et al.* 2008; Maus *et al.* 2007, 2008). This in turn prompted a renewed interest in the question of the exact nature of the sources of the lithospheric field. This is not a simple issue because, as is well known, inverting lithospheric field models in terms of magnetization models is severely limited by fundamental non-uniqueness issues (for a detailed discussion of these, see, e.g. Purucker & Whaler 2007). Thus, even if one is just interested in general statistical properties of the lithospheric and crustal magnetization (such as Jackson 1994, or Voorhies *et al.* 2002), additional *a priori* information about the nature of those sources is much needed. Of particular interest to the present study is the issue of how much of the lithospheric magnetic field signal is due to induced magnetization, as opposed to remanent magnetization. Forward modelling of the early data provided by the MAGSAT 1980 satellite concluded that induced magnetization is likely to be the main source of the largest scales of the lithospheric magnetic field (e.g. Counil *et al.* 1991, see also Maus & Haak 2002), whereas remanent magnetization is more likely to be the dominant cause of its smallest scales, at least within the oceans (e.g. Cohen & Achache 1994; Dyment & Arkani-Hamed 1998), but also perhaps even more so within the continents (Maus & Haak 2002; but see also Lesur & Gubbins 2000). First results from the Oersted mission later confirmed that view (Purucker *et al.* 2002). However, such conclusions heavily rely on the type of *a priori* information and combinations of forward and inverse modelling techniques authors use to build their magnetization model of the lithosphere.

Most recently, Hemant & Maus (2005) (building on earlier work by Hahn *et al.* 1984; Purucker *et al.* 1998) developed a more comprehensive approach. Relying on a carefully compiled database of seismic thickness of the crust, geologic and tectonic maps of the world, laboratory susceptibility values of the occurring rock types and using a geographical information system technique, they produced worldwide vertically integrated susceptibility (VIS) and remanent magnetization (VIM) grids. Starting from those *a priori* grids and using a forward modelling approach, they next showed that many of the observed lithospheric magnetic field anomalies described by the MF3 model (Maus *et al.* 2006) could be accounted for. They also showed that adjusting poorly known boundaries and the composition of the buried Precambrian provinces could efficiently reduce quite a few of the remaining discrepancies between their prediction and MF3. This is very encouraging. Their final model, however, has limitations. It does not account for all of the observed lithospheric field anomalies. It also often underestimates the magnitude of those it accounts for (as can be seen by comparing figs 5 and 18 of Hemant & Maus 2005). However, there are good reasons why this could be the case. One is that the VIM grid of Hemant & Maus (2005) assumes remanent magnetization only within the oceans. This is because very little is known about the possible structure of remanent magnetization within the continents. Yet, there is no question that there must be significant remanent magnetization there as well. Those could explain the 'missing' anomalies. Another important reason is that the VIS grid arbitrarily assumes the depth of the Moho to be equivalent to that of the Curie isotherm. But in many instances, the depth of the Curie isotherm could be significantly larger. This would then translate into larger values of the VIS than assumed by Hemant & Maus (2005) and in an increase in the value of the predicted induced magnetic signal. Comparing the spectrum of the induced lithospheric field predicted by the VIS grid of Hemant & Maus (2005) with the lithospheric field spectra estimated from CM4 (Sabaka *et al.* 2004), MF5 (Maus *et al.* 2007) and xCHAOS (Olsen & Mandea 2008), is instructive in this respect (Fig. 2). It shows that the energy of the predicted induced lithospheric field (when using xCHAOS up to degree 13 as the inducing core field model) is indeed weaker than that of the observed lithospheric field, on average by a factor of 2–3, depending on which lithospheric field model is considered. Of course, in carrying such comparisons, the remanent signal predicted by the VIM grid of Hemant & Maus (2005) should also be taken into account. But it turns out that this would not change much to the overall predicted lithospheric field spectrum (not shown). From this, we conclude first that the VIS grid of Hemant & Maus (2005) can be used to provide a first-order estimate of the minimum changes the induced

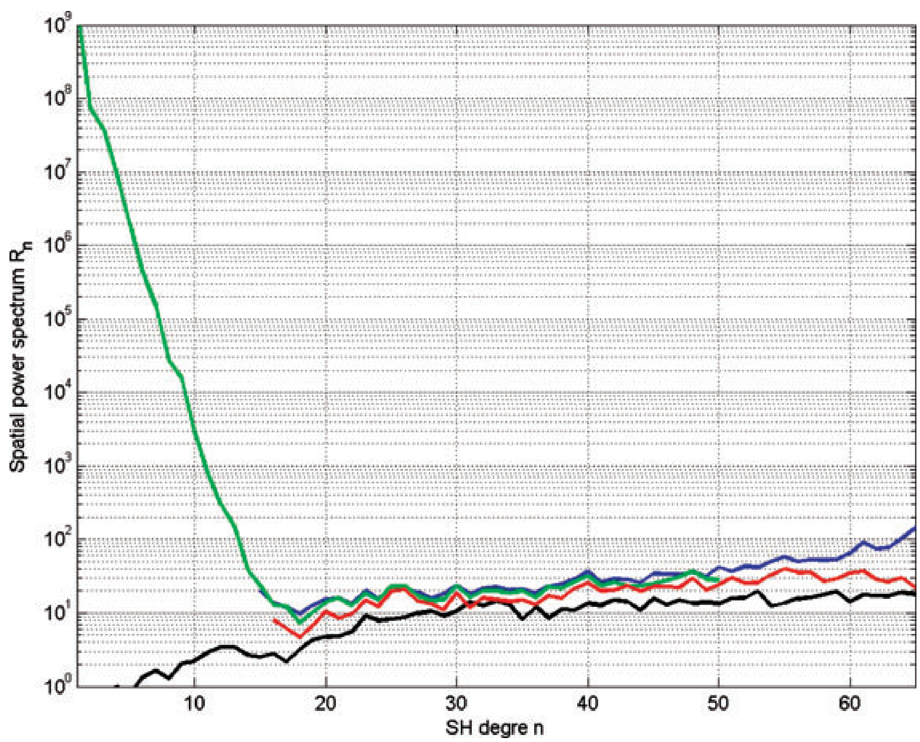


**Figure 2.** Mauersberger–Lowes spectrum of the induced lithospheric field predicted at the Earth's mean radius by the VIS grid of Hemant & Maus (2005) when using xCHAOS (up to degree 13, for epoch 2004), as the inducing field (black). For comparison, the Mauersberger–Lowes spectra of the field of internal origin at the Earth's mean radius as estimated from the CM4 model of Sabaka *et al.* (2004) (blue), the MF5 model of Maus *et al.* (2007) (red), the xCHAOS model of Olsen & Mandea (2008) (green) are also shown. Note that MF5 is only a model of the lithospheric field for degrees 16–100. Units are $(nT)^2$.

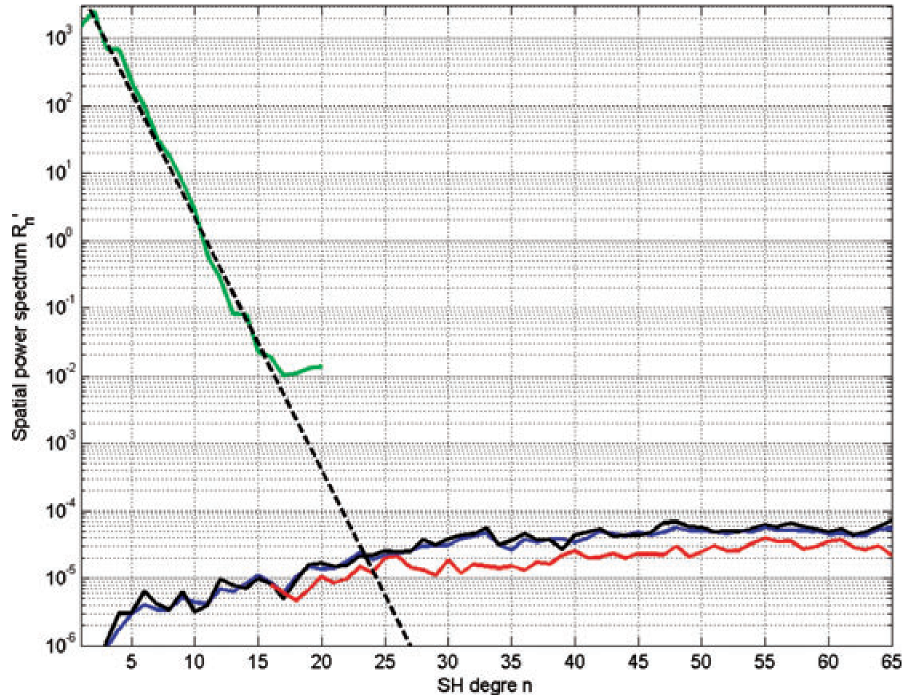


**Figure 3.** Mauersberger–Lowes spectra of the lithospheric contributions to the temporal changes of the field of internal origin at the Earth's mean radius, as predicted from the VIS grid of Hemant & Maus (2005), using xCHAOS up to degree 16 at epoch 2004, as input for the time-varying inducing field (black); the same VIS grid but using the average secular variation (between 1960 and 2002.5) up to degree 13 of CM4 (blue), using MF5 divided by 1000 yr (red). Also shown the spectrum of xCHAOS secular variation for epoch 2004 (green) and a best linear fit to this spectrum up to degree 16 (dashed, $R_n' = 10^{-0.3728n+4.0654}$). Units are (nT yr$^{-1}$)$^2$.

magnetization is currently experiencing, and second that changes two to three times more energetic could possibly occur. Those estimates can then be used to quantify the likely contributions of the lithosphere to the temporal changes of the field of internal origin.

Fig. 3 shows the Lowes–Mauersberger spectrum of those contributions for epoch 2004, which we compute from the VIS grid of Hemant & Maus (2005), using the time changing part of the core field from xCHAOS up to degree 16 as input for the time-varying inducing field (note that we checked that using xCHAOS up to degree 13 only would lead to a virtually identical spectrum, which shows that our lack of knowledge of the even higher degrees of the inducing field changes is not an issue for the present study). This figure clearly shows that lithospheric contributions are indeed very small compared with the secular variation currently resolved. But it also shows that if the regular decreasing trend observed in the secular variation spectrum of xCHAOS can be extrapolated to the next 10 degrees or so, this spectrum is bound to intersect the spectrum of the field changes produced by the lithosphere at some degree $N_C$. Fig. 3 shows that one such simple extrapolation (a best linear fit to the xCHAOS spectrum up to degree 16, as plotted in Fig. 3) predicts that this would occur for $N_C = 23$ or 24 at most.

## 3 DISCUSSION

The above result shows that the main cause of the observed changes in the field of internal origin up to some critical degree $N_C$, is indeed likely to be the secular variation of the core field, but that the signal produced by the time-varying lithospheric field is bound to dominate and conceal the time-varying core signal beyond that degree. The value we found for $N_C$ is very close to the $N_C = 22$ value, empirically predicted by McLeod (1996) by 'assuming that the root-mean-square secular variation of the crustal field is about 0.1% per year' [as stated by the author on page 2751, below equation (33b)]. This amounts to estimate the spatial spectrum of the lithospheric field changes to be that of the lithospheric field divided by (1000 yr)$^2$ [as can also be inferred from McLeod's two idealized statistical lithospheric and crustal secular variation spectra (30a) and (36a)]. That is a rough assumption but not an unreasonable one to start from. It may be viewed as equivalent to assuming that the lithospheric field is entirely of induced origin, and that the inducing field is mainly the dipole field, which indeed roughly changes on timescales of 1000 yr (as can be inferred from the square root value of the ratio $R_1/R_1'$ of the degree-one contributions to the respective Lowes–Mauersberger spectra of the field and its first time derivative, following the lines of Hulot & Le Mouël 1994). In fact, we note that making use of this assumption and of the recent lithospheric field spectrum of MF5 (Maus *et al.* 2007) would indeed lead to an estimate of $N_C$ of about 24 (also shown in Fig. 3). Note, however, that the time varying lithospheric field spectrum predicted in this way would not properly reflect the one we predict. It would have less energy, especially toward intermediate degrees (say, between 25 and 60), even though it assumes the induced lithospheric magnetization (and therefore the VIS) to be much stronger than the one we assumed. This reflects the fact that whereas the inducing field is dominated by its dipole component, its first time derivative is mainly multipolar (dominated by degree 2). Time changes of the lithospheric magnetization cannot be predicted as easily as the order of magnitude analysis of McLeod (1996) would suggest.

The main limitation to the present study is our limited knowledge of the absolute magnitude we should use for the VIS. The results we report on Fig. 3 are based on the original VIS estimate of Hemant & Maus (2005). This, as we already pointed out, leads to a low-end estimate of the lithospheric field changes spectrum and therefore to an upper bound for $N_C$. A lower bound can also be derived if we now take into account the fact, also noted earlier, that the VIS could be larger. Increasing this VIS so that the spectrum of the predicted induced lithospheric field matches that provided by CM4, MF5 or xCHAOS (up to three times more energetic) would bring $N_C$ closer to 22. Given the uncertainties involved (note that the spectra of CM4, MF5 and xCHAOS also reveals some disagreement with respect to the exact absolute magnitude of the lithospheric field itself, the origin of which is related to the way each models are derived from the data, see, e.g. Sabaka & Olsen 2006), it thus seems safe to conclude that $N_C$ should lie within the bracket 22–24.

As can be seen in Fig. 3, the maximum degree currently resolved by secular variation models (possibly degree 16, as suggested by xCHAOS) is not very far from $N_C$. Reaching the resolution required to witness the signature of the field changes produced by the lithospheric field is, however, unlikely to be an easy task. To assess the extent to which this could be achieved some day, it is worthwhile noting that the induced lithospheric field changes we predict are bound to essentially occur in an additive way on at least several decades. This can be shown by inspecting the spectrum of the 'average' rate of lithospheric field change the VIS model of Hemant & Maus (2005) predicts over 42.5 yr (between 1960 and 2002.5), when using CM4 (Sabaka *et al.* 2004) as input for the inducing field. As can be seen in Fig. 3, this spectrum is very close to the spectrum of the 'annual' lithospheric change predicted in 2004, when using xCHAOS as the inducing field. Thus, short-term and 40-yr time-averaged lithospheric field changes essentially occur at similar (but of course not identical) rates. This result is not as surprising as one might think. It simply reflects the fact that time changes in the induced magnetization, at all length scales, are mainly due to the interaction of the VIS lithospheric structure with the dominant large-scale secular variation (with a maximum degree 2 component, as already noted), which itself essentially acts in an additive way over decades. This result is, in fact, encouraging because xCHAOS (built from only 9 yr of satellite data and 12 yr of observatory data, Olsen & Mandea 2008) suggests that an absolute change of 1.2 nT can be detected with the help of current satellites [as inferred from 0.13 nT yr$^{-1}$ × 9 yr, given that the xCHAOS degree 16 secular variation energy is of order 0.018 (nT yr$^{-1}$)$^2$]. If the same amount of absolute change could be detected from longer time-series, this then suggests that about 250 yr of similar quality data could be enough to possibly sense the $2 \times 10^{-5}$ (nT yr$^{-1}$)$^2$ energy the VIS model of Hemant & Maus (2005) predicts for the degree 23 lithospheric field changes. This, we must admit, is still a very long call. However, if we also take into account the fact that the VIS model of Hemant & Maus (2005) is a low estimate, and that the actual degree 23 energy could be three times larger, this number could reduce to about 150 yr. In addition, we may also reasonably expect future missions such as the ESA Swarm mission, soon to be launched (Friis-Christensen *et al.* 2006; Olsen *et al.* 2006b), to perform better and detect smaller field changes than the 1.2 nT we assumed for this calculation. Any gain in reducing this value would then translate into the same gain in reducing the time needed to detect lithospheric field changes. A modest factor three could for instance further reduce this time to 50 yr. This is the typical time during which we just showed lithospheric field changes would indeed occur in an additive way, thus making its detection possible. In fact, it is worth finally pointing out that lithospheric field changes happen to be significantly more energetic at high degrees than at low degrees (as is clear from the trends of the spectra shown in Fig. 3), and that detection of even smaller scale local lithospheric changes from combined satellite and ground data could turn out to be much more feasible.

**Table 1.** Minimum field changes a 10-yr-long satellite mission would need to resolve for the degree *n* core-field secular variation to possibly be detected.

| Degree ($n$) | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|
| ΔB (nT) | 1.12 | 0.73 | 0.48 | 0.31 | 0.20 | 0.13 | 0.086 | 0.056 |

This exciting possibility, which, however, has no implication for the intermediate scales of interest to the present study, is discussed in details in a separate study (Thébault *et al.* 2009).

The above reasoning shows that only multidecadal averages of the field changes produced by the lithospheric magnetization might be detected some day, and that this possibility relies on the fact that those changes act in an additive way on decade timescales. Unfortunately, small-scale core-field secular variation does not act in the same way. Statistical analysis of the historical behaviour of the best known degrees of the core field indeed show that the field fluctuates on timescales that decrease fast with the spherical harmonic degree considered (Hulot & Le Mouël 1994; Hongre *et al.* 1998). Recent empirical laws suggest that the timescales involved for each degree $n$ field is such that $\tau(n) = 890\, n^{-1.35}$ yr (Olsen *et al.* 2006a) or $\tau(n) = 1000\, n^{-1.45}$ yr (Holme & Olsen 2006; see also Lesur *et al.* 2008, for yet another very comparable empirical law). This essentially implies that the degree 16 core-field secular variation is likely to change its sign after a time $\tau(16)$, of order of 18– 21 yr, whereas degrees closer to $N_C$ could change their sign after only a time $\tau(23)$, of order of 10–13 years. These numbers are interesting. They explain how the detection of the secular variation up to degree 16 can be achieved from 9 yr of satellite data and 12 yr of observatory data (of course, to within some unavoidable smoothing of the weakest and smallest scales of the modelled secular variation). Unfortunately, the values of $\tau(16)$ and $\tau(23)$ also show that increasing the observational time period to more than say, 20 yr, would probably not help, because the cumulative signal would likely be significantly averaged out. It thus follows that the strategy we suggested could be used to possibly detect the signature of the lithospheric field changes some day, cannot be used to recover core-field secular variation with degrees higher than 16. Only an improvement in the intrinsic quality of satellite missions and in data analysis techniques, especially with respect to the proper identification and removal of fields of external origin, might help. Table 1 gives estimates of the absolute field changes ($\Delta B$, between start and end), one 10-yr-long mission would need to resolve, to possibly detect core-field secular variation up to a given degree $n$ (as computed from $\Delta B = (R'_n)^{0.5} \times 10$ yr, where $R'_n$ is based on the linear extrapolation of the secular variation spectrum plotted in Fig. 3). These estimates show that reaching the largest degrees of the core-field secular variation not concealed by the crust ($n = 22$ and perhaps $n = 23$) would require a minimum factor 14 improvement in resolution (again assuming that, as xCHAOS suggests, degree 16 can already be resolved over such a duration). This is very challenging. A more plausible improvement by just a factor two or three could, however, bring degrees 17 and 18 within reach.

We therefore conclude that although lithospheric field changes must dominate temporal changes in the field of internal origin beyond degree $N_C$ (of minimum value 22, maximum value 24) and might be detected some day, thanks to its additive nature, degree 18 is probably the highest degree of the core-field secular variation one could possibly resolve in the next decade.

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## REFERENCES


Cohen, Y. & Achache, J., 1994. Contribution of induced and remanent magnetization to long-wavelength oceanic magnetic anomalies, *J. geophys. Res.,* **99,** 2943–2954.

Counil, J., Cohen, Y. & Achache, J., 1991. The global continent–ocean magnetization contrast, *Earth planet. Sci. Lett.,* **103,** 354–364.

Dyment, J. & Arkani-Hamed, J., 1998. Contribution of lithospheric remanent magnetization to satellite magnetic anomalies over the world's oceans, *J. geophys. Res.,* **103,** 15 423–15 441.

Eymin, C. & Hulot, G., 2005. On core surface flows inferred from satellite magnetic data, *Phys. Earth planet. Inter.,* **152,** 200–220.

Fournier, A., Eymin, C. & Alboussiere, T., 2007. A case for variational geomagnetic data assimilation: insights from a one-dimensional, nonlinear, and sparsely observed MHD system, *Nonlinear Process. Geophys.,* **14,** 163–180.

Friis-Christensen E., Lühr, H. & Hulot, G., 2006. *Swarm*—a constellation to study the Earth's magnetic field, *Earth Planets Space,* **58,** 351–358.

Hahn, A., Ahrendt, H. , Meyer, J. & Hufen, J.-H., 1984. A model of magnetic sources within the Earth's crust compatible with the field measured by the satellite Magsat, *Geol. Jahrb., Reihe A,* **75,** 125–156.

Hemant, K. & Maus, S., 2005. Geological modeling of the new CHAMP magnetic anomaly maps using a geographical information system technique, *J. geophys. Res.,* **110,** B12103, doi:10.1029/2005JB003837.

Holme, R. & Olsen, N., 2006. Core surface flow modelling from high-resolution secular variation, *Geophys. J. Int.,* **166**(2), 518–528, doi:10.1111/j.1365-246X.2006.03033.x.

Hongre, L., Hulot, G. & Khokhlov, A., 1998. An analysis of the geomagnetic field over the past 2000 yr, *Phys. Earth planet. Inter.,* **106,** 311–335.

Hulot, G. & Le Mouël, J.L., 1994. A statistical approach to the Earth's main magnetic field, *Phys. Earth planet. Inter.,* **82,** 167–183.

Hulot, G., Le Mouël, J.L. & Wahr, J., 1992. Taking into account truncation problems and geomagnetic model accuracy in assessing computed flows at the core-mantle boundary, *Geophys. J. Int.,* **108,** 224–246.

Hulot, G., Eymin, C., Langlais, B., Mandea, M. & Olsen, N., 2002. Smallscale structure of the geodynamo inferred from Oersted and Magsat satellite data, *Nature,* **416,** 620–623.

Hulot, G., Sabaka, T. & Olsen, N., 2007. The present field, in *Geomagnetism, Treatise Geophys.,* Vol. 5, pp. 33–75, ed. G. Schubert, Elsevier, New York.

Jackson, A., 1994. Statistical treatment of crustal magnetization, *Geophys. J. Int.,* **119,** 991–998.

Jackson, A., 2003. Intense equatorial flux spots on the surface of the earth's core, *Nature,* **424**(6950), 760–763.

Langel, R.A. & Estes, R.H., 1985. The near-Earth magnetic field at 1980 determined from MAGSAT data, *J. geophys. Res.,* **90,** 2495–2510.

Lesur, V. & Gubbins D., 2000. Using geomagnetic secular variation to separate remanent and induced sources of the crustal magnetic field, *Geophys. J. Int.,* **142,** 889–897.

Lesur, V., Wardinski, I. Rother, M. & Mandea M., 2008. GRIMM: The GFZ Reference Internal Magnetic Model based on vector satellite and observatory data, *Geophys. J. Int.,* **173,** 382–394, doi:10.1111/j.1365-246X.2008.03724.x.

Liu, D., Tangborn, A. & Kuang, W., 2007. Observing system simulation experiments in geomagnetic data assimilation, *J. geophys. Res.,* **112,** B08103, doi:10.1029/2006JB004691.

Lowes, F.J., 1974. Spatial power spectrum of the main geomagnetic field, and extrapolation to the core, *Geophys. J. R. astr. Soc.,* **36,** 717–730.

Mauersberger, P., 1956. Das Mittel der Energiedichte des geomagnetischen Hauptfeldes an der Erdoberfläche und seine säkulare Änderung, *Gerlands Beitr. Geophys.,* **65,** 207–2015.

Maus, S., & Haak, V., 2002. Is the long wavelength crustal magnetic field dominated by induced or by remanent magnetisation?, *J. Ind. Geophys. Union,* **6**(1), 1–5.

Maus, S., Rother, M., Holme, R., Lühr, H., Olsen, N. & Haak, V., 2002. First scalar magnetic anomaly map from champ satellite data indicates weak lithospheric field, *Geoph. Res. Lett.,* **29**(14), 1702, doi:10.1029/2001GL013685.

Maus, S., McLean, S., Dater, D., Lühr, H., Rother, M., Mai, W. & Choi, S., 2005. NGDC/GFZ candidate models for the 10th generation International Geomagnetic Reference Field, *Earth Planets Space,* **57,** 1151–1156.

Maus, S., Rother, M., Hemant, K., Stolle, C., Lühr, H., Kuvshinov, A. & Olsen, N., 2006. Earth's lithospheric magnetic field determined to spherical harmonic degree 90 from CHAMP satellite measurements, *Geophys. J. Int.,* **164,** 319–330, doi:10.1111/j.1365-246X.2005.02833.x.

Maus, S., Lühr, H., Rother, M., Hemant, K., Balasis, G., Ritter, P. & Stolle, C., 2007. Fifth-generation lithospheric magnetic field model from CHAMP satellite measurements, *Geochem. Geophys. Geosyst.,* **8,** Q05013, doi:10.1029/2006GC001521.

Maus, S. *et al*., 2008. Resolution of direction of oceanic magnetic lineations by the sixth-generation lithospheric magnetic field model from CHAMP satellite magnetic measurements, *Geochem. Geophys. Geosyst.,* **9,** Q07021, doi:10.1029/2008GC001949.

McLeod, M.G., 1996. Spatial and temporal power spectra of the geomagnetic field, *J. geophys. Res.,* **101,** 2745–2763.

Neubert, T. *et al*., 2001. Ørsted satellite captures high-precision geomagnetic field data, *EOS, Trans. Am. geophys. Un.,* **82**(7), 81–88.

Olsen, N., 2002. A model of the geomagnetic field and its secular variation for epoch 2000 estimated from Ørsted data, *Geophys. J. Int.,* **149**(2), 454–462.

Olsen, N. & Mandea, M., 2008. Rapidly changing flows in the Earth's core, *Nature Geosci.,* **1,** 390–394.

Olsen, N., Lühr, H., Sabaka, T.J., Mandea, M., Rother, M., Tøffner-Clausen, L. & Choi, S., 2006a. CHAOS—a model of the Earth's magnetic field derived from CHAMP, Ørsted, and SAC-C magnetic satellite data, *Geophys. J. Int.,* **166**(1), 67–75, doi:10.1111/j.1365-246X.2006.02959.x.

Olsen N. *et al*., 2006b. The swarm End-to-End mission simulator study: a demonstration of separating the various contributions to Earth's magnetic field using synthetic data, *Earth Planets Space,* **58**(4), 359–370.

Pais A. & Jault, D., 2008. Quasi-geostrophic flows responsible for the secular variation of the Earth's magnetic field, *Geophys. J. Int.,* **173,** 421–443, doi:10.1111/j.1365-246X.2008.03741.x.

Purucker, M. & Whaler, K., 2007. Crustal magnetism, in *Geomagnetism, Treatise Geophys.,* Vol. 5, pp. 195–235, ed. G. Schubert, Elsevier, New York.

Purucker, M. E., Langel, R.A., Rajaram, M. & Raymond, C., 1998. Global magnetization models with a priori information, *J. geophys. Res.,* **103,** 2563–2584.

Purucker, M., Langlais, B., Olsen, N., Hulot, G. & Mandea, M., 2002. The southern edge of cratonic North America: evidence from new satellite magnetometer observations, *Geophys. Res. Lett.,* **29**(15), 8000, doi:10.1029/2001GL013645.

Reigber, C., Lühr, H. & Schwintzer, P., 2002. CHAMP mission status, *Adv. Space Res.,* **30,** 129–134.

Sabaka, T.J. & Olsen, N., 2006. Enhancing comprehensive inversions using the *Swarm* constellation, *Earth Planets Space,* **58,** 371–395.

Sabaka, T.J., Olsen, N. & Purucker, M.E., 2004. Extending comprehensive models of the Earth's magnetic field with Ørsted and CHAMP data, *Geophys. J. Int.,* **159,** 521–547.

Thébault, E., 2006. Global lithospheric magnetic field modelling by successive regional analysis, *Earth Planets Space,* **58,** 485–495.

Thébault, E., Hemant, K., Hulot, G. & Olsen, N., 2009. On the geographical distribution of induced time-varying magnetic fields, *Geophys. Res. Lett.,* **36,** L01307, doi:10.1029/2008GL036416.

Thomson, A. & Lesur, V., 2007. An improved geomagnetic data selection algorithm for global geomagnetic field modelling, *Geophys. J. Int.,* **169,** 951–963, doi:10.1111/j.1365-246X.2007.03354.x.

Voorhies, C.V., Sabaka, T.J. & Purucker, M., 2002. On magnetic spectra of Earth and Mars, *J. geophys. Res.,* **107**(E6), 5034, doi:10.1029/2001JE001534.